Wiley Online Library
Early View publication on www.wileyonlinelibrary.com
(issue and page numbers not yet assigned;
citable using Digital Object Identifier – DOI)

Phys. Status Solidi C, 1–4 (2014) / DOI 10.1002/pssc.201300472

physica status solidi c
www.pss-c.com
current topics in solid state physics

Leakage-current reduction and improved on-state performance of Au-free AlGaN/GaN-on-Si Schottky diode by embedding the edge terminations in the anode region

Jie Hu[*,1,2], Silvia Lenci[1], Steve Stoffels[1], Brice De Jaeger[1], Guido Groeseneken[1,2], and Stefaan Decoutere[1]

[1] imec vzw, Kapeldreef 75, 3001 Heverlee, Belgium
[2] Departement Elektrotechniek – ESAT-MICAS, Katholieke Universiteit Leuven, Kasteelpark Arenberg 10, postbus 2440, 3001 Heverlee (Leuven), Belgium

Received 23 August 2013, revised 24 September 2013, accepted 29 November 2013
Published online 30 January 2014

Keywords AlGaN/GaN-on-Si, Schottky barrier diode, edge termination, leakage current, forward voltage

* Corresponding author: e-mail hujie@imec.be, Phone: +32 16283275 Fax: +32 16281844

AlGaN/GaN Schottky barrier diodes (SBDs) have been fabricated on GaN-on-Si wafers (8-inch) with Au-free CMOS compatible technology. Two types of Edge Terminations have been investigated to suppress the leakage current with the conventional AlGaN/GaN Schottky Barrier Diodes fabricated on the same wafer as a reference. The External Edge Terminated-SBD (EET-SBD) shows a trend of reduction in leakage current by scaling down the spacing between the edge termination and the Schottky contact. By embedding the edge terminations inside the anode region named Gated Edge Terminated-SBD (GET-SBD), four orders of magnitude reduction in leakage current has been observed experimentally compared with the reference. Furthermore, anode recess was performed and its influences on both on- and off-state characteristics were studied. The recessed EET-SBD shows lower leakage current than the non-recessed one. The forward voltage drop in EET-SBD appears to be degraded by recess. The recessed GET-SBD features the lowest leakage (1 µA/mm at V_{AC} of -600 V) and improved on-state performance (with V_F of 1.15 V). With Anode-to-Cathode distance (L_{AC}) of 10 µm, a breakdown voltage over 600 V in all three architectures has been achieved in both recessed and non-recessed wafers.

© 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction AlGaN/GaN-on-Si Schottky barrier diodes (SBDs) are attractive for high-power switching applications owing to their superior properties including fast switching speed, low on-state resistance, as well as large breakdown field strength [1]. In order to achieve low static power loss of the diode in a switching circuit, low reverse leakage current ($I_{Leakage}$) and low forward voltage drop (V_F) are required.

Various approaches have been proposed to suppress the leakage current, e.g., Schottky junction terminations [2], dual-metal combining with high Schottky barrier metal and low Schottky barrier metal in the anode [3], the use of AlGaN back-barrier [4], etc. Additionally, recessed anode topology was reported to achieve low turn-on voltage without sacrificing neither the on-state resistance nor the reverse blocking capability [5].

In this work, we have optimized, simultaneously, the reverse leakage current and forward voltage drop of Au-free AlGaN/GaN SBDs on Si by investigating two types of edge terminations and different anode recess conditions. These AlGaN/GaN SBDs have been fabricated and co-integrated together with AlGaN/GaN Metal-Insulator-Semiconductor High Electron Mobility Transistors (MISHEMTs) by using Au-free CMOS-compatible technology on 8-inch GaN-on-Si wafers [6].

2 Device fabrication
By using Metalorganic Chemical Vapor Deposition (MOCVD), AlGaN/GaN active layers were grown on 8-inch GaN-on-Si wafers. The epitaxial structure consists of a 17 nm $Al_{0.21}Ga_{0.79}N$ barrier, a 150 nm unintentionally doped (UID) GaN channel, a buffer layer (400 nm

© 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

$Al_{0.74}Ga_{0.26}N$/ 400 nm $Al_{0.44}Ga_{0.56}N$/1800 nm $Al_{0.21}Ga_{0.79}N$), and a 200 nm AlN nucleation layer on *p*-type Si (111) substrate. The whole epitaxial stack was encapsulated by 140 nm rapid thermal chemical vapor deposition (RTCVD) Si_3N_4 layer. The median two-dimensional electron gas (2DEG) sheet resistances measured from a passivated TLM structure were 442.5 and 471.6 Ω/sq for non-recessed and recessed wafers, respectively. SBDs were then fabricated on the wafer with nitrogen-based implantation as inter-device isolation. A Au-free Ti/Al/Ti/TiN-based stack was used for the cathode contact formation, which was annealed at 550 °C. The median contact resistances were 1.8 and 1.5 Ω·mm for non-recessed and recessed wafers, respectively. A stack of 20 nm TiN/20 nm Ti/ 250 nm Al/ 20 nm Ti/ 60 nm TiN was deposited to define the anode contact.

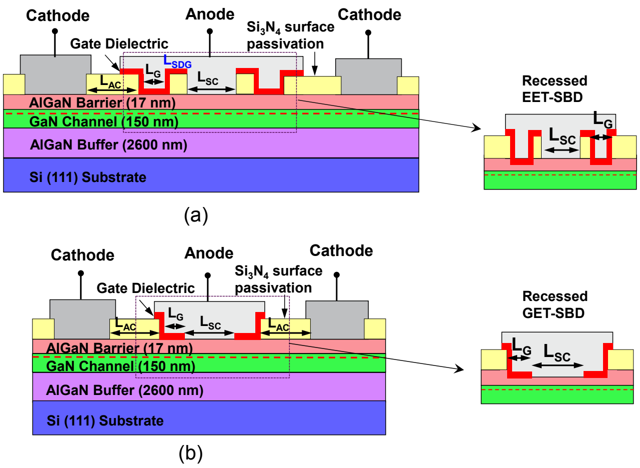

Figure 1 Cross-sectional schematics of AlGaN/GaN-on-Si SBDs with edge terminations: (a) External Edge Terminated-SBD (EET-SBD), and (b) Gated Edge Terminated-SBD (GET-SBD). The recessed architectures are shown to the right.

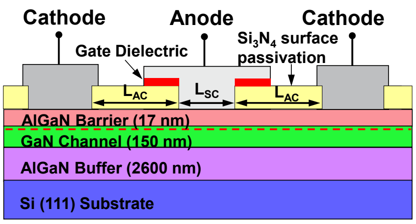

Figure 2 Cross-sectional schematics of conventional SBD, there is 1 µm overhang at the Schottky edge on top of the Si_3N_4 passivation layer.

In the case that anode recess was applied, the 17 nm-thick AlGaN barrier was recessed with 12 nm by using a BCl3 reactive ion etching process. Consequently 5 nm AlGaN barrier was left in (part of) the anode region for both external edge terminated-SBD (EET-SBD) and gated edge terminated-SBD (GET-SBD) architectures, as shown in Fig. 1. An edge termination (5 nm Si_3N_4/10 nm Al_2O_3 and 15 nm Si_3N_4 gate dielectric with dimension L_G for non-recessed and recessed wafer, respectively) was fabricated beside the Schottky contact at a distance of L_{SGD} for EET-SBD architecture. A compact version was also fabricated by embedding the edge terminations inside the anode trench as in the case of GET-SBD. Conventional SBDs were processed on the same wafer as reference with cross-sectional schematic in Fig. 2.

3 Results and discussion On-wafer DC characterization was performed on all the diodes by grounding the Cathode and biasing the Anode from -100 V to 3 V using an Agilent 4073 Ultra Advanced Parametric Tester. All the tested devices have *anode finger width* = 100 µm and 1-µm anode metal overlapping toward the cathode. The Schottky contact length (L_{SC}) is 9 µm, 6 µm, and 5 µm for SBD, GET-SBD and EET-SBD, respectively. The standard length of the edge termination (L_G) is 1.5 µm for GET-SBD and EET-SBD. The current is normalized to the *anode finger width*. The turn-on voltage and forward voltage are defined at current density of 1 mA/mm and 100 mA/mm, respectively.

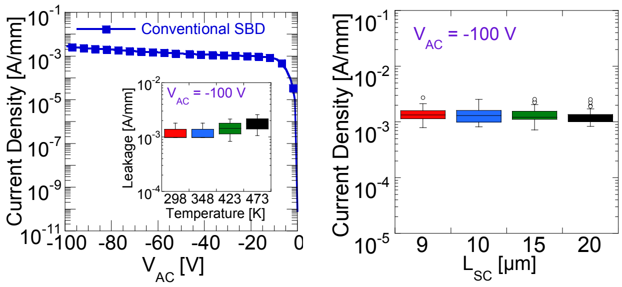

Figure 3 Reverse characteristics (left) of reference SBD. The inset graph shows the leakage current at V_{AC} = - 100 V at different temperatures. Statistical plot (right) of leakage current at V_{AC} = -100 V with different Schottky contact lengths (L_{SC}).

The reverse characteristics of reference SBD is plotted in Fig. 3 (left), the inset graph shows the leakage current at anode-to-cathode voltage (V_{AC}) of -100 V at different temperatures. It can be seen that the leakage current is as high as 1 mA/mm and weakly dependent on the temperature from 298 K to 473 K, which means that tunnelling current is a major component in the leakage at V_{AC} = -100 V. Figure 3 (right) clarifies the statistical plot of leakage current at V_{AC} of -100 V with different L_{SC}, showing that the leakage current is a perimeter-effect rather than area-scaling effect as the current density is invariant with different L_{SC}. Initial TCAD simulations were done to visualize the electric field distribution in the AlGaN barrier at V_{AC} of -100 V (Fig. 4). It is observed that a peak electric field (~ 8 MV/cm) is located at the corner of the Schottky contact which was assumed to contribute to the perimeter-scaling leakage current in the conventional SBD.

© 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

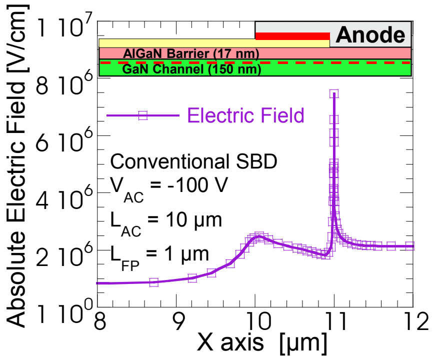

Figure 4 Distribution of electric field inside AlGaN barrier with distance of 0.5 nm to the anode contact at V_{AC} = -100 V.

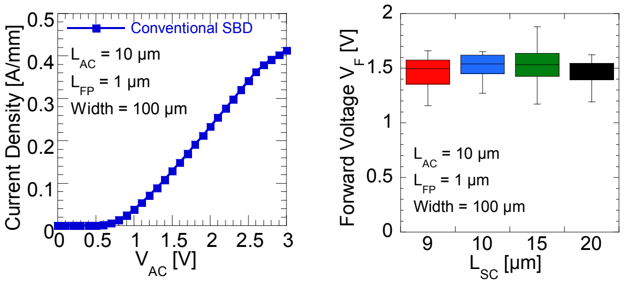

Figure 5 Forward characteristics (left) of reference SBD and statistical plot (right) of forward voltage with different Schottky contact length (L_{SC}).

Figure 5 (left) shows the forward characteristics of conventional SBD as the reference. The forward voltage of conventional SBD is displayed in Fig. 5 (right) with different L_{SC}. The results show that the forward voltage V_F is around 1.5 V and independent of the Schottky contact length for the reference diode.

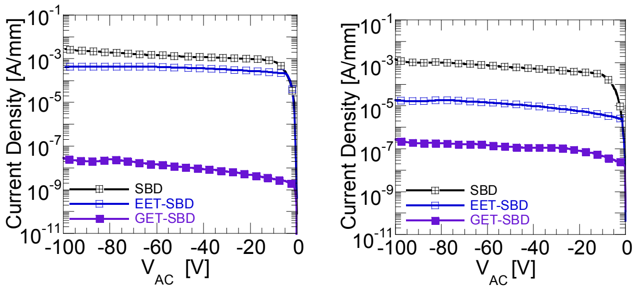

Figure 6 Reverse characteristics of reference SBD, EET-SBD, and GET-SBD for non-recessed wafer (left) and recessed wafer (right).

The reverse characteristics of reference SBD, EET-SBD, and GET-SBD for non-recessed and recessed wafer are illustrated in Fig. 6. Non-recessed EET-SBD shows slightly lower leakage current than SBD, while non-recessed GET-SBD demonstrates four orders of magnitude reduction in leakage. Recessed EET-SBDs show two orders of magnitude reduction as compared with the reference SBDs due to the additional AlGaN barrier recess at the edge terminations which reduces the 2 DEG density. The recessed GET-SBD still features the lowest leakage current.

The spacing between edge termination and Schottky contact plays a fundamental role between EET-SBD and GET-SBD. GET-SBD can be thought of having L_{SDG} = 0, which experimentally shows significant reduction of leakage current. To understand the different leakage behaviour between these two architectures, leakage current at V_{AC} = -100 V was measured for EET-SBD with different L_{SDG}. The GET-SBD and the reference SBD are also plotted in the same graph for comparison. As shown in Fig. 7, by scaling down the dimension L_{SDG} from 4 µm to 0.25 µm, the leakage current in EET-SBD can be reduced by one order of magnitude. However, a significant drop in leakage can be achieved by embedding the edge termination inside the anode trench as in the GET-SBD architecture. This trend has be observed for both non-recessed and recessed wafers, and recessed GET-SBD architecture does not show degradation of leakage current at V_{AC} = -100 V.

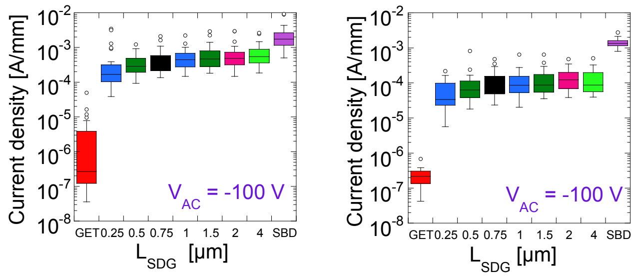

Figure 7 Statistical box plots of reverse leakage current at V_{AC} = -100 V for EET-SBD with L_{SDG} variations in non-recessed (left) and recessed (right) wafer, respectively.

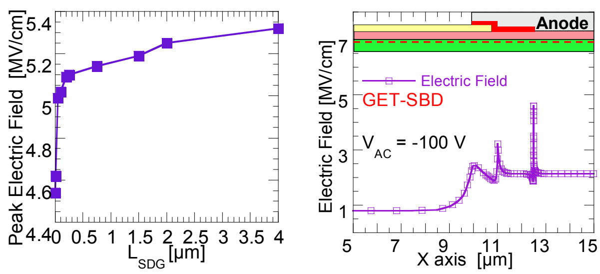

Figure 8 The peak value of electric field (left) at the corner of the Schottky contact with different L_{SDG} dimensions in EET-SBD and electric field distribution (right) in AlGaN barrier in GET-SBD.

As speculated, the leakage current in off-state is related to the peak electric field at the corner of Schottky contact. A TCAD simulation shows that the value of peak electric field at the corner Schottky contact in non-recessed EET-SBD slightly goes down by reducing the dimension L_{SDG}, a big drop in the peak electric field is achieved with L_{SDG} = 0 as in the compact GET-SBD architecture. Figure 8 (right) shows the electric field distribution along the AlGaN barrier with a distance of 0.5 nm to the anode contact in the GET-SBD. As compared with the result from reference

© 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

SBD, the peak value of electric field at the corner of the Schottky contact drops from 8 MV/cm to 5 MV/cm. There is another peak electric field observed near the Schottky contact in GET-SBD which comes from the redistribution of the electric field from the edge terminations. From simulations and experimental results, we can conclude that the leakage current is highly dependent on the peak electric field located at the corner of the Schottky contact, embedding the edge terminations inside the anode trench enables a reduction of the peak electric field and suppression of the leakage current.

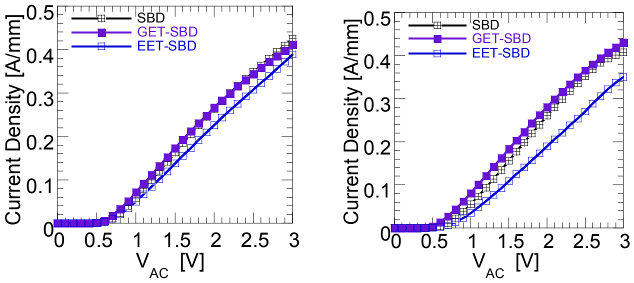

Figure 9 Forward characteristics of reference SBD, GET-SBD, and EET-SBD (L_{AC} = 10 µm) for non-recessed (left) and recessed wafers (right).

Typical forward characteristics of the non-recessed SBD, GET-SBD, and EET-SBD with anode-to-cathode distance (L_{AC}) of 10 µm are shown in Fig. 9 (left). The turn-on voltage for three SBDs is around 0.6 V, and EET-SBD shows larger on-state resistance (R_{ON}) compared with GET-SBD and SBD because of its higher access resistance due to the external edge terminations. For the recessed wafer as shown in Fig. 9 (right), GET-SBD shows improvements of on-state characteristics. EET-SBD has a

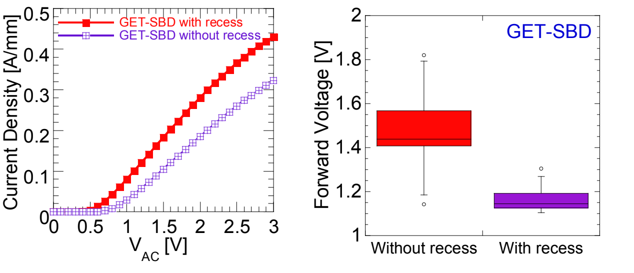

Figure 10 Typical forward (left) characteristics of non-recessed and anode recessed GET-SBD (L_{AC} = 10 µm); a box plot (right) shows the statistical distribution of the forward voltage in non-recessed and anode recessed GET-SBD.

degradation of R_{ON}, this can be due to AlGaN barrier recessing process done at the edge terminations. Figure 10 displays the on-state characteristics of non-recessed and recessed GET-SBDs. The forward voltage of GET-SBD drops from 1.45 to 1.15 V by recessing the AlGaN barrier as shown in Fig. 10 (right). Besides, AlGaN barrier recessing results in a tighter distribution of forward voltage.

Breakdown measurements were performed for both non-recessed and recessed diodes including three different architectures with L_{AC} = 10 µm. In the data presented in Fig. 11, it can be seen than all diode topologies have reached breakdown voltage over 600 V. The GET-SBD shows a leakage current as low as 1 µA/mm at V_{AC} = -600 V for both non-recessed and recessed structures.

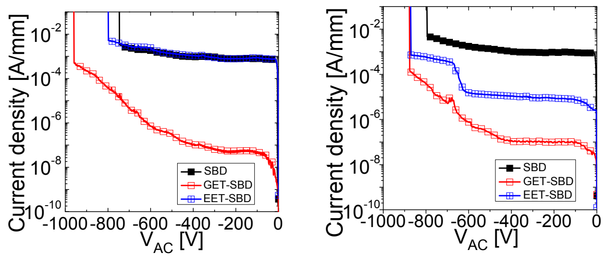

Figure 11 Breakdown measurement on non-recessed SBD, GET-SBD, and EET-SBD (left); breakdown measurement on SBD, recessed GET-SBD, and recessed EET- SBD (right).

4 Conclusion

Au-free, CMOS-compatible AlGaN/GaN Schottky barrier diodes have been processed on 8-inch Si wafer. Three different architectures have been investigated and their DC characteristics have been compared. It has been demonstrated that embedding the edge terminations inside the anode trench (GET-SBD) has more effective Schottky contact shielding effect than EET-SBD, resulting in a significant drop of leakage current. GET-SBD maintains leakage within 1 µA/mm at V_{AC} = -600 V. The forward voltage for the GET-SBD can be improved from 1.45 V to 1.15 V by anode recessing. It has been demonstrated that on-state performance together with the leakage current for AlGaN/GaN diodes can be simultaneously optimized by recessing GET-SBD anode without breakdown voltage degradation.

References

[1] N.-Q. Zhang, B. Moran, S. P. Denbaars, U. K. Mishra, X. W. Wang, and T. P. Ma, Phys. Status Solidi A **188**, 213 (2001).
[2] Z. He, United States Patent Application Publication, No. US 2011/0133251 (2011).
[3] N. Ikeda, J. Li, S. Kato, M. Masuda, and S. Yoshida, Proc. Furukawa Rev. Conf., 1–6 (2006).
[4] E. Bahat-Treidel, O. Hilt, A.Wentzel, J. Würfl, and G. Tränkle, Phys. Status Solidi C **10**(5), 849 (2013).
[5] E. Bahat-Treidel, O. Hilt, R. Zhytnytska, A.Wentzel, C. Meliani, J. Würfl, and G. Tränkle, IEEE Electron Device Lett. **33**(3), 357 (2012).
[6] S. Lenci, B. De Jaeger, L. Carbonell, J. Hu, G. Mannaert, D. Wellekens, S. You, B. Bakeroot, and S. Decoutere, IEEE Electron Device Lett. **34**(8), 1035 (2013).

© 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim